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Measurement of Cross Sections for the $^{63}Cu(\alpha,\gamma)^{67}Ga$ Reaction from 5.9-8.7 MeV

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Abstract. We have measured cross sections for the $^{63}Cu(\alpha,\gamma)^{67}Ga$ reaction in the 5.9-8.7 MeV energy range using an activation technique. Natural Cu foils were bombarded with alpha beams from the 88″ Cyclotron at Lawrence Berkeley National Laboratory (LBNL). Activated foils were counted using gamma spectrometry system at LBNL's Low Background Facility. The $^{63}Cu(\alpha,\gamma)^{67}Ga$ cross-sections were determined and compared with the latest NON-SMOKER theoretical values. Experimental cross sections were found to be in agreement with theoretical values.

INTRODUCTION

Cross-section measurements for charged-particle capture reaction on nuclei heavier than iron are important for nucleosynthesis studies [1] and for testing statistical model predictions. The inner zones of supernovae, where temperatures exceed 10^9 K are places where proton and alpha particle reactions on medium to heavy nuclei may be important in determining the mix of elements and isotopes that emerge from such stellar explosions. Within the last few years, some proton capture cross sections in the A=90-100 mass region [2-4] and alpha capture on ^{144}Sm, ^{70}Ge, and ^{96}Ru isotopes [5-7] have been reported. Experimental alpha capture cross sections on ^{96}Ru and ^{144}Sm were reported to be about 2.5 and 5-7 times lower than the latest theoretical values respectively. An earlier measurement of alpha capture on ^{40}Ca also found cross sections to be about 3-5 times lower than the theoretical predictions [8]. However, the experimental S-factor values for the $^{70}Ge(\alpha,\gamma)^{74}Se$ reaction were in agreement with statistical model calculations [6]. It is important to investigate alpha capture cross sections for different mass regions to test the theoretical models. Rapp *et al.* [7] indicated a possible deficiency in the theoretical treatment of the alpha channels for the mass region 100 and suggested additional alpha induced cross section measurements over a wider mass range for understanding and improving the situation.

Here we report the measured cross sections for the $^{63}Cu(\alpha,\gamma)^{67}Ga$ reaction in the 5.9-8.7 MeV energy range using an activation technique. Experimental procedure and comparison of the measured data with the latest theoretical values are presented and discussed.

EXPERIMENTAL PROCEDURE

Natural Cu foil of thickness ~1 mg/cm^2 used in this experiment were purchased from ACF-Metals, Tucson, Arizona. The foils were floated on water from glass slides and mounted on circular aluminum holders. Three stacks of targets each having four ^{nat}Cu and one ^{nat}Ti foil of thickness 2.7 mg/cm^2 were prepared. The target stacks were mounted on a thick water-cooled copper block that also served as a beam stop. Two stacks were irradiated for an hour with alpha beam of energies 8.8 MeV and 7.9 MeV from the 88″ Cyclotron at LBNL. The beam current was 1μA. The third stack was irradiated for 6 hours with 7.0 MeV beam energy and 0.1 μA current. The uncertainty in the beam energy was about 1%. The incident alpha beam energy on the successive foils was calculated by

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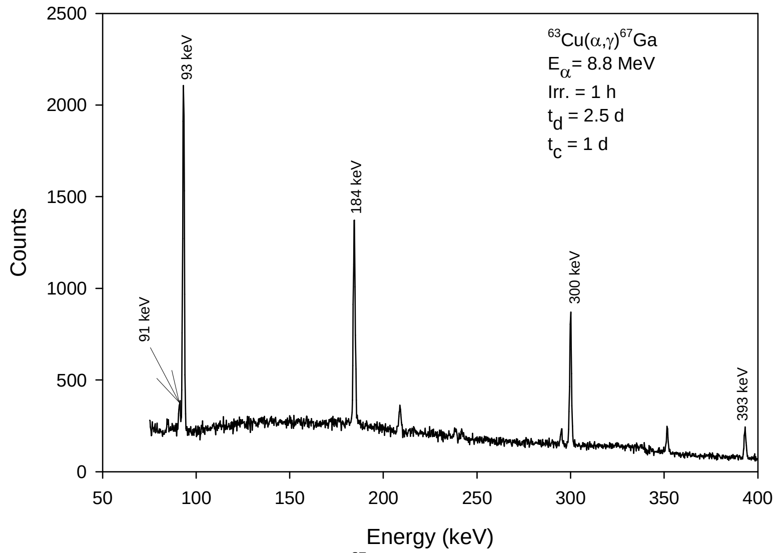

FIGURE 1. A partial HPGe γ-ray spectrum of ^{67}Ga characteristic γ lines (t_d and t_c = decay and counting time).

energy loss through Cu foils using dE/dx, values estimated using the TRIM (the Transport of Ions in Matter) code [9]. On average, the loss per Cu foil was about 300 keV. The beam current was integrated using a Brookhaven Instruments Corporation Integrator.

The titanium foil, at the end of each stack, was used for checking the current integration by the ^{48}Ti(α,n)^{51}Cr reaction and as a catcher of the recoil ^{67}Ga radioisotopes to estimate the recoiled fraction. The monitoring reaction cross section was compared with published experimental data [10].

Following each irradiation, the copper targets were counted immediately using an HPGe detector to measure the ^{68}Ga activity, produced through the ^{65}Cu(α,n)^{68}Ga reaction. All the copper foils were later recounted for longer periods of time to measure the ^{67}Ga activity using another HPGe detector, 80% relative efficiency, at LBNL's Low Background Facility (LBF). A partial HPGe γ-ray spectrum collected at the LBF is shown in Figure 1 for the characteristic γ-energies of ^{67}Ga. The ^{67}Ga radioactivity in samples bombarded with the two highest beam energies was sufficiently high to count at 25 cm and 15 cm away from the detector end cap. However, for the lowest beam energy, samples were counted at the end cap surface of the HPGe detector. Efficiency calibration of the HPGe detectors was done using calibrated point sources of ^{22}Na, ^{54}Mn, ^{57}Co, ^{60}Co, ^{109}Cd, ^{133}Ba, and ^{137}Cs gamma sources purchased from Isotope Products Laboratories. The efficiency curve for the surface counting position was generated using count ratios of single gamma sources at surface position and 25 cm away and following the procedure of reference [11]. Single gamma lines 88.0 keV, 320.1 keV, 661.4 keV, and 834.8 keV from ^{109}Cd, ^{51}Cr, ^{137}Cs, and ^{54}Mn, respectively, were used. The ^{51}Cr source was available from the current experiment.

All gamma spectra were analyzed using ORTEC Gamma Vision software. The 91 keV and 93 keV gamma lines of ^{67}Ga were slightly overlapped in the tail. The combined area of these two peaks was used together to determine the ^{63}Cu(α,γ)^{67}Ga cross section. The cross sections were deduced from the well known activation equation:

$$A_o = n\sigma\phi\left(1 - e^{-\lambda t}\right) \qquad (1)$$

Where, A_o = product radioisotope activity at the end of irradiation, n = number of target nuclides, σ = cross section, ϕ = number of incident particles, and $\left(1 - e^{-\lambda t}\right)$ = build up factor for a decay constant λ and irradiation time t.

The activity, A_o, at the end of irradiation was deduced from the measurement using the following equation:

$$A_o = \lambda N_o = \lambda C \Big/ \left\{ I_\gamma \varepsilon \left(e^{-\lambda(t_{cs} - t_{ie})} - e^{-\lambda(t_{ce} - t_{ie})} \right) \right\} \qquad (2)$$

Where, t_{cs}, t_{ce}, t_{ie} are counting start, counting end, and irradiation end times, respectively, C = net area under the peak for a counting duration (t_{cs} - t_{ce}), I_γ = gamma ray intensity, and ε = detector peak efficiency.

TABLE 1. Nuclear data of the product radioisotopes used in this experiment [12]

Nuclear reaction	Half life	E_γ (keV) (I_γ%) uncertainty for the least significant digit(s)
$^{63}Cu(\alpha,\gamma)^{67}Ga$	3.26 d	91.3(3.16 ± 9), 93.3(39.2 ± 10), 184.6(21.2 ± 3), 300.2 (16.8 ±22), 393.5(4.68 ± 6)
$^{65}Cu(\alpha,n)^{68}Ga$	67.63 min	1077.4 (3.0 ± 3)
$^{48}Ti((\alpha,n)^{51}Cr$	27.7 d	320.1 (9.92 ± 5)

Cross sections of the $^{63}Cu(\alpha,\gamma)^{67}Ga$ reaction were deduced using all ^{67}Ga γ-rays and found to be statistically consistent to each other. Nuclear data for the product nuclei used in this experiment is presented in Table 1. Reported cross sections for the $^{63}Cu(\alpha,\gamma)^{67}Ga$ reaction in this paper are deduced using the 184 keV γ-ray. In all gamma spectra, this peak had smooth tailing on both sides with statistically reasonable peak area. Absolute γ-ray intensities of ^{67}Ga are deduced in this work, considering the recent ^{67}Ga decay data [13] and using relative γ-ray intensities from Ref. [14]. We used 184 keV γ-ray intensity of 20.7 ± 0.1%, about 2 percent lower than the value in Ref. [12]. There was an overlapping bombarding energy for the last foil of the 1st stack and the 1st foil of the 2nd stack. The agreement between these two cross sections for the common energy was excellent. This served as a cross check for the two different sets of irradiation for the $^{63}Cu(\alpha,\gamma)^{67}Ga$ reaction measurement.

Titanium foils were counted after about 7 days at the LBF using an HPGe detector for ^{51}Cr and the recoiled ^{67}Ga activities. This length of decay period allowed the 91.3 keV and 93.3 keV ^{67}Ga peaks to appear in the spectra. Recoiled ^{67}Ga activity was determined using equation (1) and (2) and was found to be about 10%-14% in this experiment. Assuming a uniform ^{67}Ga recoil out of the successive foils in the stack, a correction of 12% was made for the first Cu foil ^{67}Ga activity in each stack. Measured cross sections for the $^{48}Ti(\alpha,n)^{51}Cr$ reaction were compared with the published experimental data [10] for beam current calibration. The comparisons were in good agreement for 8.8 MeV and 7.9 MeV beam current. However, for the 7.0 MeV energy beam, Ti foil interacted with incident alpha beam energy of 5.7 MeV and energy loss through the foil was about 1.3 MeV. Published cross section for the monitoring reaction in this range was partially available, so the calibration of the beam current for this beam energy was incomplete. However, employing other cross checks, such as simultaneous $^{65}Cu(\alpha,n)^{68}Ga$ cross section measurement and comparison with known experimental results, we are confident with the beam current integration technique.

Considering all uncertainties of detector efficiency calibration, target foil thickness, beam current, counting statistics, decay data, and recoil fraction, we report 15% uncertainties for the measured cross sections.

RESULTS AND DISCUSSION

Measured cross sections for the $^{63}Cu(\alpha,\gamma)^{67}Ga$ reaction are presented in Table 2. In Figure 2, measured values are presented along with the latest theoretical values of the NON-SMOKER statistical model [15]. Theoretical data points were obtained from URL using the finite range droplet model (FRDM) masses. These data points were not available in regular intervals in the studied energy range, however, from Figure 2, it can be seen that the agreement between the experimental and theoretical data are reasonably good for the $^{63}Cu(\alpha,\gamma)^{67}Ga$ reaction cross sections.

TABLE 2. Measured cross sections for the $^{63}Cu(\alpha,\gamma)^{67}Ga$ reaction

Beam Energy (MeV)	Cross section (mb)
8.65 ± 0.09	1.08 ± 0.16
8.37 ± 0.08	1.04 ± 0.16
8.08 ± 0.08	0.93 ± 0.14
7.80 ± 0.08	0.69 ± 0.10
7.54 ± 0.08	0.41 ± 0.06
7.24 ± 0.07	0.26 ± 0.04
6.99 ± 0.07	0.18 ± 0.03
6.88 ± 0.07	0.13 ± 0.02
6.56 ± 0.07	0.07 ± 0.01
6.22 ± 0.06	0.026 ± 0.004
5.88 ± 0.06	0.012 ± 0.002

The comparison of measured $^{65}Cu(\alpha,n)^{68}Ga$ cross-sections in this work with those of Stelson *et al.* [16] were found to be excellent. This agreement provides an indication of the experimental integrity for the reported $^{63}Cu(\alpha,\gamma)^{67}Ga$ cross-section measurement.

Based on the present results and those from studies of the $^{70}Ge(\alpha,\gamma)^{74}Se$ reaction [6], it appears that the NON-SMOKER theoretical calculations of (α,γ) cross sections in the mass region of A=60-70 are in

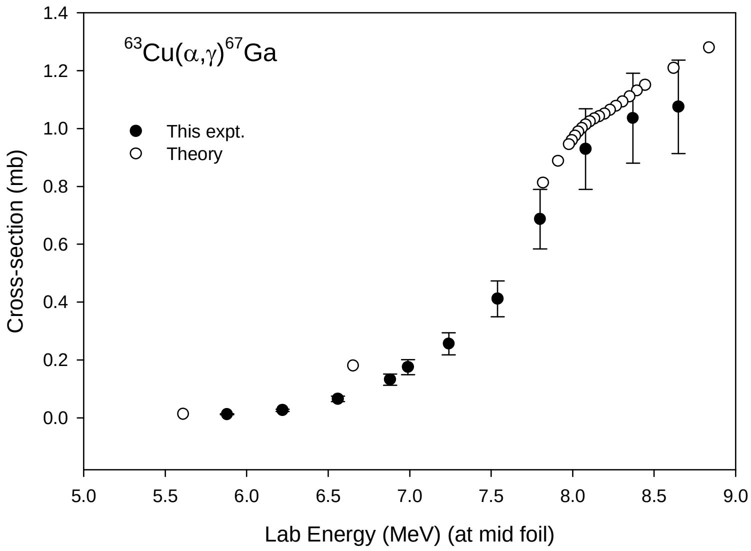

FIGURE 2. Experimental and theoretical cross sections for the $^{63}Cu(\alpha,\gamma)^{67}Ga$ reaction.

reasonably good agreement with the experimental data.

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